Medium-scale experiments of fire warehouses

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This study, funded by AFILOG, focuses on the threat caused by the large heat releases from warehouse fires. The objective is to improve the understanding of the propagation of the fire inside the warehouse and to quantify the heat fluxes experienced in the vicinity of the warehouse. This will ultimately help refine the modelling tool presently employed by INERIS [1] to evaluate the thermal effects from warehouse fires on nearby populations and/or other industrial installations. Such an evaluation is important, for example, to help land-use planning.

Medium-scale experiments of warehouse fires (see Figures 1 and 2) were conducted in a purposedly built 3 metres high building with a section of 4.3×4 m^2. One side of the building was open and the top was covered with a plywood. This roof was meant to help the propagation of the fire and then disappear so as to be representative of a fully-developed fire in a large warehouse. Four steel racks were set up inside the building on which were stacked 40 cm $\times$ 40 cm $\times$ 50 cm high wood cribs made of pine sticks. To monitor the fire propagation, 52 measurements of temperature were undertaken with thermocouples throughout the storage area. Outside the building, heat fluxes were measured at a total of 20 locations in front of the building and on the two sides. The heat flux metres were located at different distances from the building and different heights. Videos were recorded from 4 cameras around the building and an infrared camera. The images allowed to time events such as the appearance and propagation of smoke, the collapse of the roof and stacks and to determine the shape and size of the flames. The fire was set by a burner located beneath the third rack towards the rear of the building. The heat release rate from the fire was deduced from the measurement of the total mass loss.

The influence of a number of parameters on the longitudinal fire propagation along the racks, the lateral propagation from one rack to another and the shape and height of the flame once the roof collapsed was investigated. These parameters were the stockage compacity, the thickness of the roof and the number of rack shelves. The most important results will be presented and compared where appropriate to previous work, in particular to studies on fire propagation in warehouses [eg. 2] Thermal effects of fire warehouses on their surroundings have been less studied and will be analysed here in some details. In particular, the measured heat fluxes will be compared with the values predicted by the in-house tool FNAP. The limitations of FNAP which assumes a solid parallelepipedic flame will be discussed in the light of the observations of the shapes and heights of the flames. Future steps aimed to improve FNAP and to carry out full-scale experiments will be briefly presented.

KEYWORDS: fire, warehouse, experiment, thermal radiation

INTRODUCTION

This study, funded by AFILOG, focuses on the threat caused by the large heat releases from warehouse fires. The objectives are two-fold: to improve the understanding of the propagation of the fire inside the warehouse and to quantify the heat fluxes experienced in the vicinity of the warehouse. This will ultimately help refine the modelling tool presently employed by INERIS [1] to evaluate the thermal effects from warehouse fires on nearby populations and/or other industrial installations. Such an evaluation is important, for example, to help land-use planning.

The influence of a number of parameters on fire propagation, the shape and height of the flame once the roof collapsed and the radiative heat fluxes emitted in the vicinity of the building was investigated. These parameters were the storage compacity, the number of rack tiers and the level of containment (roof thickness and draft curtain depth).

Previous work [for example 2,3] has investigated the effect of various parameters on the fire propagation in warehouses. However, very little work has been carried out on the effect of these parameters on the radiative thermal effects further away from the fire.

EXPERIMENTAL SET-UP

Medium-scale experiments of warehouse fires (see Figure 1) were conducted in a purposedly built 3 metres high building with a section of 4.3×4 m^2. One side of the building was open with a 0.6 m deep draft curtain made of a 5 mm thick plywood. The top of the building was covered with a 5 mm thick plywood. This thin roof was meant to help the

Figure 1. Picture of the experimental set-up (of the 3-tier, highly compact storage with a low containment level)

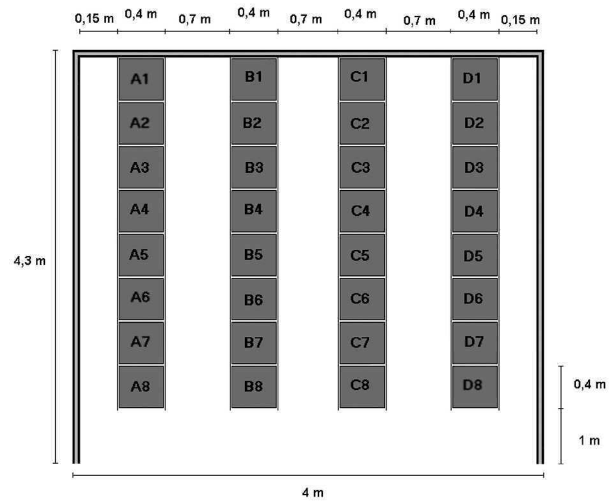

Figure 2. Sketch of the experimental set-up

propagation of the fire and then disappear so as to be representative of a fully-developed fire in a large warehouse. Four steel racks were set up inside the building on which were stacked 40 cm × 40 cm × 50 cm high wood cribs made of pine sticks. The racks were fixed to the building so that they could not collapse. This was safer but it should be born in mind that it is not representative of a real fire in a warehouse. The fire was set by a burner located beneath the third rack towards the rear of the building.

The heat release rate ($\dot{Q}$) from the fire was deduced from the measurement of the total mass loss ($\dot{m}$). Unfortunately, the humidity rate (h) of the wood employed was not negligible and varied with the scenario. This was taken into account by employing the following equation:

$$\dot{Q} = (1 - h)\dot{m}\Delta H_c \tag{1}$$

This is based on the assumption that the heat release rate will be reduced proportionally to the mass loss throughout the duration of the fire. In reality, the initial mass loss will be due mainly to the vaporisation of water and relatively little to the burning of wood. Once the water is vaporised, the mass loss will correspond to the burning of wood. So the assumption made will tend to make the heat release start a bit early and may under-predict the maximum heat release rate. In some cases, when all the scenarios on which conclusions are drawn have a similar humidity rate, the presence of humidity has little influence on the outcome of this study. If otherwise, this is highlighted.

Videos were recorded from 4 cameras around the building and an infrared camera. The images allowed to time events such as the appearance and propagation of smoke, the collapse of the roof and stacks and to determine the shape and size of the flames. To monitor the fire propagation, 48 measurements of temperature were undertaken with thermocouples, which were uniformly distributed throughout the storage area as can be seen in Figure 2. In addition, 4 thermocouples were placed underneath the roof.

Outside the building, heat fluxes were measured at 9 locations in front of the building, 7 locations on one side and 4 on the other side. Below are considered the measurements obtained the fluxmetres located in front of the building at a height of 1.5 m, corresponding roughly to the heat received by the head of a standing person. The fluxes were measured at five distances from the building: 3, 4, 6, 8.5 and 11 m. The time-dependent fluxes are characterised by three values: the maximum flux, the time Tmax at which the maximum flux is reached. It is these three characteristic values that are compared. The maximum flux is plotted against the distance from the building for the different scenarios whilst the values of the characteristic times are given for each scenario since they depend very little on the distance from the building.

The influence of a number of parameters on the fire propagation and thermal radiative effects around the building were studied. These parameters were the storage compacity, the number of tiers of the racks and the level of containment of the building.

EFFECT OF THE STORAGE COMPACITY

The effect of the storage compacity was investigated by comparing the case where the wood cribs are stacked next to each other with the one where a space of 10 cm is left between them. This was done for a 3-tier and a 4-tier storage. The experimental conditions are summarised in Table 1.

The lower the compacity, the sooner the maximum heat release rate is reached (see Figure 3). Also, the peak is much higher in the case of a 4-tier storage whilst it is independent of compacity for a 3-tier storage. The faster propagation of the fire in the case of a storage of low compacity is

Table 1. Experimental conditions for studying the influence of the storage compacity

Compacity: space between the cribs	Number of tiers	Roof thickness	Draft curtain depth	Humidity rate	Storage height	Initial mass of dry wood
No space (high)	3	5 mm	0.6 m	23.2%	2 m	1850 kg
10 cm (low)				16.2%		1480 kg
No space (high)	4			20.6%	2.7 m	2623 kg
10 cm (low)				17.1%		1915 kg

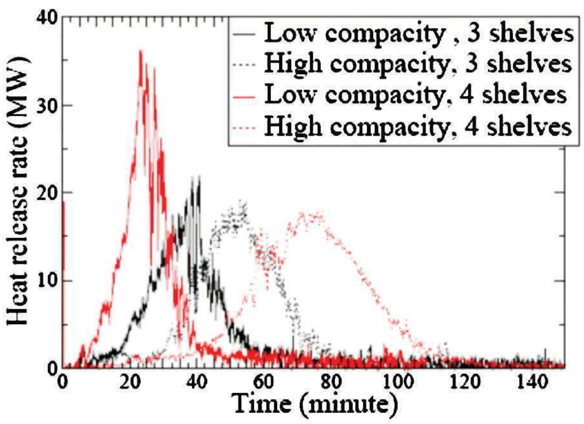

Figure 3. Comparison of the heat release rates for the storage compacity

confirmed by the events observed (see Figure 4): a hole appears more rapidly in the roof and the fire propagates quicker to the other racks, thus increasing the power of the fire. In the case of low compacity, air can more easily circulate between the cribs, making more oxygen available thus facilitating the burning of the stored goods. This trend was also observed at a smaller scale [4]. Other studies [5,6] have also shown that the propagation, especially in the vertical direction, depended on the storage compacity.The fire of the low compact 4-tier storage may be particularly fast and powerful due to the larger supply in both oxygen and combustible compared to the other cases. The humidity rates varied greatly between the storages of low and high compacity for a given number of tiers and were higher for the storages of high compacity. It is believed that qualitatively, the trend would remain the same if the humidity rates were similar. However, quantitatively, the differences between the peak times may be higher and the differences between the peak values may be smaller.

As for the radiative effect from the fire, the maximum heat flux received at the front of the building is higher for the 4-tier storage of low compacity than the one of high compacity but the trend is opposite for the 3-tier storage (see Figure 5). In fact, for the 3-tier storage the peaks of the heat release rate for the low and highly compact storage are of the same order but the flame was smaller and narrower for the storage of high compacity. The heat radiated from this flame was thus higher. For the 4-tier storage, the size of the flames were similar for the two different compacities and the peak heat release rate was higher for the low compact storage, leading to a higher radiative flux. On the other hand, for both the 3-tier and 4-tier storages, the times Tmax at which the maximum heat flux are reached (see Table 2) are higher in the case of the high storage compactity. The latter are related to the times at which the peak heat release rates are reached.

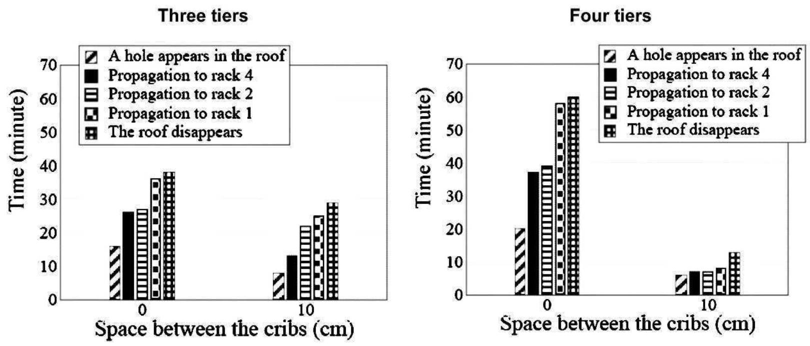

Figure 4. Effect of the number of tiers on the fire propagation

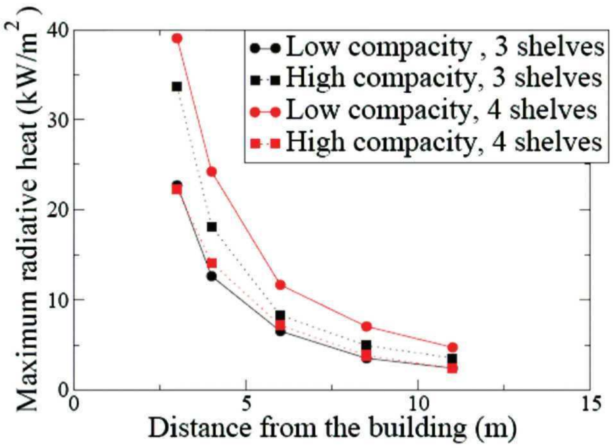

Figure 5. Effect of the storage compacity on the radiative heat

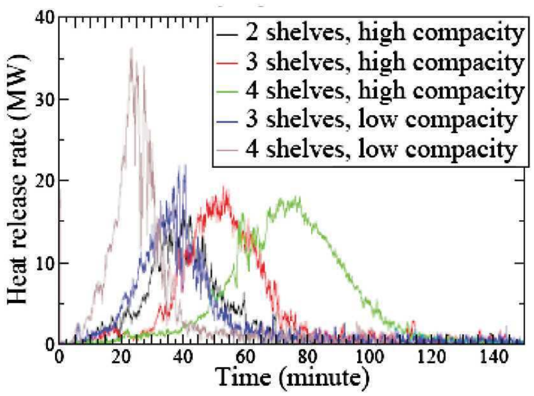

Figure 6. Comparison of the heat release rates for storages with different number of tiers

EFFECT OF THE NUMBER OF TIERS OF THE RACKS

The number of tiers varied from 2 to 4 tiers in the case of a high compact storage and from 3 to 4 in the case of a low compact storage (see Table 3).

For the highly compact storage, the maximum heat release rate is about the same no matter the number of tiers but the time at which it is reached increases with the number of tiers (see Figure 6). It seems that the increased amount of wood available due to the additional tiers does not burn faster, maybe because the supply of oxygen is limited by the storage compacity. So the fire is of similar power but lasts longer when there are more tiers (see Figure 7). On the other hand, for the low compact storage, the additional tier leads to a faster propagation of the fire and the maximum heat release rate is reached relatively early, about 25 minutes after the ignition of the fire. In this case, the fire is not limited by the supply of oxygen and the additional wood increases the power of the fire which is shorter in duration.

The maximum radiative heat fluxes received at the front of the builing are of the same order for the highly packed storage, with slightly higher values for the 3-tier storage than the other two (see Figure 8). For the lower storage compacity, the radiative fluxes emitted by the fire of the 4-tier storage are higher than the ones from the 3-tier storage.This follows the trend observed for the maxima of the heat release rates. The times at which the highest radiative flux is received correspond for all cases to the times at which the peak release rates are reached, with a few minutes' delay.

Table 2. Effect of the storage compacity on Tmax

	Compacity	Tmax (minutes)
3tiers	Low	40
	High	60
4 tiers	Low	25
	High	85

EFFECT OF THE CONTAINMENT

The level of containment was investigated: the thickness of the roof was increased from 5 to 15 mm and the height of the draft curtain from 0.6 to 1.2 m. Two experiments were conducted with a 4-tier highly compact storage (see Table 5).

The behaviour of the fire was drastically different between the two levels of containment: a flashover happened about 20 minutes after the fire started when the building had the highest level of containment. That moment corresponded to the peak of the heat release rate which neared 40 MW and was the highest value of all scenarios. The rapid propagation due to the flashover can be seen in the series of major events shown in Figure 9 which happened within the first 20 minutes compared to 60 minutes

Table 3. Experimental conditions for studying the influence of the number of rack tiers

Number of tiers	Compacity: space between the cribs	Roof thickness	Draft curtain depth	Humidity rate	Storage height	Initial mass of dry wood
2	No space (high)	5 mm	0.6 m	13.3%	1.35 m	1565 kg
3				23.2%	2 m	2410 kg
4				20.6%	2.7 m	3303 kg
3	10 cm (low)			16.2%	2 m	1767 kg
4				17.1%	2.7 m	2310 kg

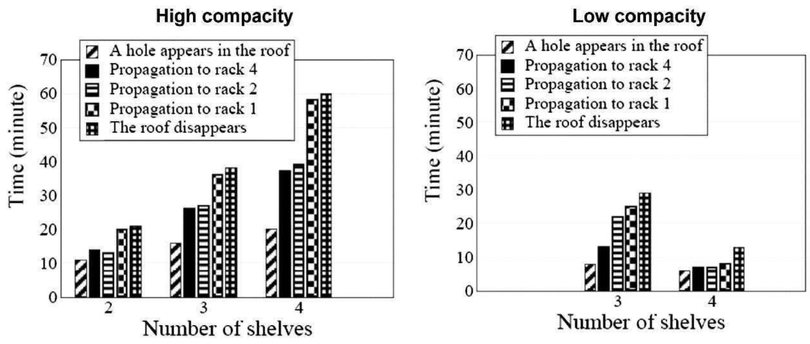

Figure 7. Effect of the number of tiers on the fire propagation

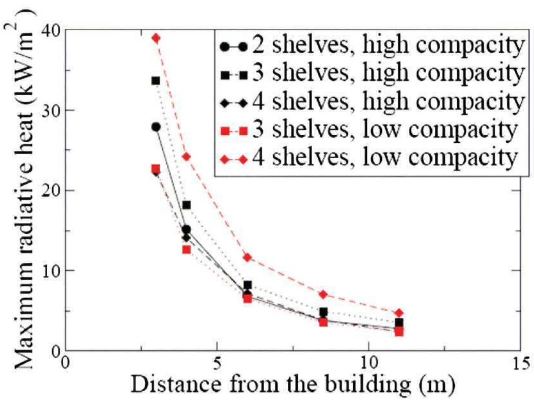

Figure 8. Effect of the number of tiers on the radiative heat

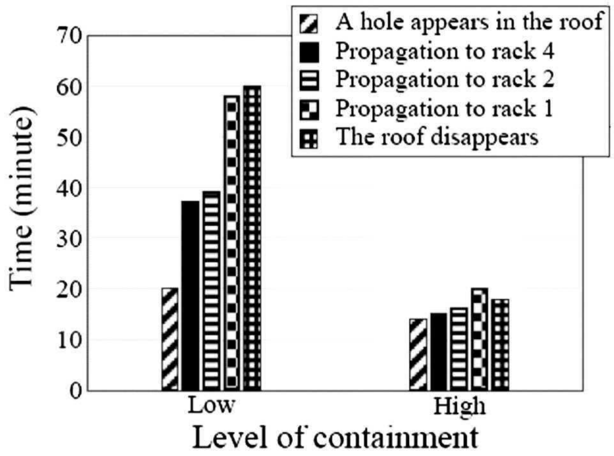

Figure 9. Effect of the number of tiers on the fire propagation

in the case of a lower containment. The fire was also observed to be more homogeneous than for any of the other scenarios with a flame that had a shape closer to a parallelepiped whilst in the other cases, the flame had a triangular shape. The humidity rates of the two scenarios under investigation here were quite different. The propagation of

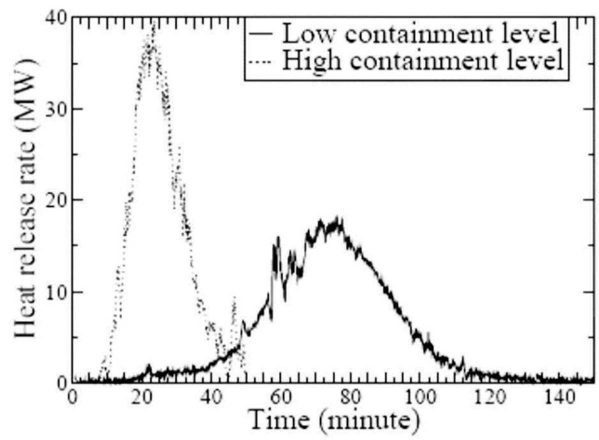

Figure 10. Effect of the number of tiers on the heat release rate

Table 4. Effect of the number of tiers on Tmax

	Number of tiers	Tmax (minutes)
High compacity	2	42
	3	60
	4	85
Low compacity	3	40
	4	25

Table 5. Experimental conditions for studying the level of containment

Roof thickness	Draft curtain depth	Number of tiers	Compacity: space between the cribs	Humidity rate	Storage height	Initial mass of dry wood
5 mm	0.6 m	4	No space (high)	20.6	2.7 m	2623 kg
15 mm	1.2 m			10.6	2.7 m	2515 kg

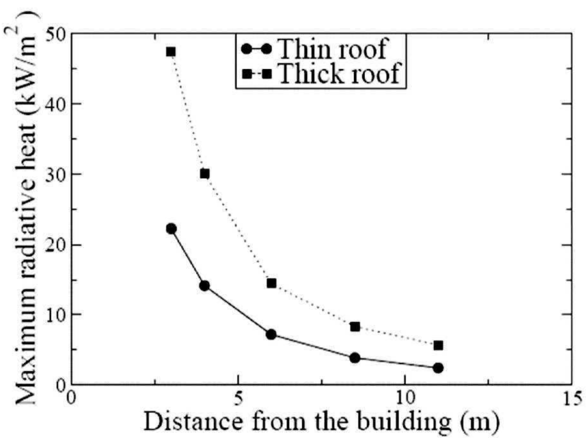

Figure 11. Effect of the level of containment on the radiative heat

the fire for the low containment case is likely to have been slowed down by the presence of humidity. However, none of the other cases, that all had a low level of containment, led to a flashover. It is thus believe that the flashover is mainly caused by the relatively high level of containment: the heat from the fire and inflammable gases accumulate in the building and at some point take fire.

The radiative heat fluxes received in front of the building are much higher in the case of a high level containment than in the case of a lower containment level (see Figure 11). They are in fact the highest values measured among all the scenarios. Ten metres away from the building, the difference between the low and high level of containment is still significant, of the order of 3 kW/m^2. This is consistent with the larger amount of heat released by the fire. It is also likely that the rectangular instead of triangular shape of the flame contributed too to the high radiative fluxes. The times at which the maximum radiative fluxes are reached correspond to the times at which the peaks of the heat release rate are reached.

CONCLUSION AND FUTURE WORK

This study showed that the storage compacity and the number of tiers both affect interactively the fire propagation and the heat radiated from the fire. The lower the compacity, the faster the propagation of the fire. However, this trend is more or less emphasised depending on the number of tiers. Reciprocically, when the storage has a low compacity, it is well ventilated and the heat release rate increases with the number of tiers as well as the fire propagation. The fire is more violent and shorter. On the contrary, when the storage has a high compacity, and is thus less ventilated, increasing the number of tiers results in a fire of similar

Table 6. Effect of the containment level on Tmax

Containment level	Tmax
Low	85
High	26

strength that lasts longer. Reinforcing the enclosure of the building has also the effect to increase the strength of the fire, to the extent in this study that a flashover happened.

The effects of these parameters on the radiated heat away from the fire followed the trend of the heat released by the fire for the time at which the maximum radiative heat is received. However, the amount of radiative heat received does not necessary follow the trend of the heat released: it also depends on the shape and size of the flame. The latter was found to have a triangular shape in all scenarios but the case of a high level of containment. The height and width varied.

The tools usually employed to predict the thermal radiative effects of a fire on the surroundings are based on the assumption that the flame is a solid parallelepiped. It is thus expected to provide conservative, but not accurate, predictions for most of the cases investigated here. Improvement will need to be made to refine the predictions. INERIS plan to undertake full-scale experiments to check if the trends observed here are the same and to employ a three-dimensional numerical tool to predict the shape of the flame and calculate the radiative effects. Both the full-scale measurements and three-dimensional predictions will help further develop the simple and practical tools for predicting thermal radiative effects.

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